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Multiparticle Production through Isoscalar Clusters*

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ABSTRACT

The isoscalar cluster model for multiparticle production has been extended to include clusters of A_2 meson pairs in addition to previously studied ρ-ρ and σ clusters. The production of each type of cluster is given by an energy dependent Poisson distribution. The Poisson parameters determined from the charged particle multiplicity distributions indicate that the inclusion of A_2-A_2 clusters does not improve the fit to the data. The predictions of the model for n_o n_-, $f^2_{-,-}$, and $f^2_{o,o}$ compare favorably to the experimental values.

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DISCLAIMER

1. Introduction

The availability of experimental data has generated a great deal of interest in the distribution of charged and neutral particles produced in high energy collisions. A number of models [1-12] have been developed attempting to explain these observed multiplicities.* In this paper we report on a study of the cluster model for multiparticle production. Previous isoscalar cluster model studies have considered σ and $\rho-\rho$ clusters decaying into two and four pions respectively. We have added A_2-A_2 clusters that decay into six pions and have incorporated an energy dependent Poisson probability for the production of each type of cluster.

The isoscalar cluster model for production of particles in the central rapidity region is supported by studies of two particle rapidity correlations and the distribution of charge transfer between c.m. hemispheres. [15] A simple picture of this mode of particle production can be developed using the multiperipheral model with Pomeron exchange. In this picture, the quantum numbers of the incident particles are carried off by the decay products of fragmentation produced clusters at each end of the multiperipheral chain. Such events are outside the scope of our model and must be described by a second, diffractive component of multiparticle production.

The assumed independence of cluster production led us to choose the Poisson distribution for its description. The Poisson

*For a history of cluster models, see reference [12] and the references cited therein.

parameter (i.e., the average number of clusters) was given a logarithmic energy dependence because of its linear relation to the average number of charged particles produced and the latter's good empirical description [13-14]:

$$\langle n_{ch} \rangle = a + b \ln s. \tag{1-1}$$

The details of the model are described in Sec.II and the results of the fit to the charged multiplicity data are discussed in Sec.III. Section IV contains our conclusions.

2. Description of Model

We assume that non-diffractive particle production consists of the production of uncorrelated isoscalar clusters of three types that have only pions as their ultimate decay products. The probability of producing each type of cluster is Poisson with an energy dependent mean of the form

$$\lambda_i = a_i \ln (s/s_i)\, \theta(s - s_i) \tag{2-1}$$

The constants a_i are determined by the data, and each s_i is given by

$$s_i = 2 m_p + m_i \tag{2-2}$$

where m_i is the mass of the respective cluster. This form for λ_i cuts off production of a cluster below its threshold and provides for logarithmic growth of the average number of particles produced. The three types of clusters we consider in this paper are termed (a) σ clusters, (b) ρ-ρ clusters, and (c) A_2-A_2

clusters. Both the σ and ρ-ρ clusters have been studied previously [1-4], but for completeness they are fully described here.

A. σ -Clusters*

Each σ cluster decays into either a π^+-π^- pair or a π^o-π^o pair. From isospin conservation, the respective probabilities are 2/3 and 1/3. Thus, for k_1 σ clusters, the probability of producing u_1 π^+-π^- pairs and v_1 π^o-π^o pairs is a binomial distribution:

$$P_{k_1}(u_1,v_1) = \frac{k_1!}{u_1!\,v_1!}\left(\frac{2}{3}\right)^{u_1}\left(\frac{1}{3}\right)^{v_1} \tag{2-3}$$

with $u_1 + v_1 = k_1$. Combining this with the Poisson distribution for producing k_1 σ clusters,

$$P(k_1) = e^{-\lambda_1}\lambda_1^{k_1}\Big/k_1! \tag{2-4}$$

gives $P_1(u_1,v_1)$, the probability of producing u_1 π^+-π^- pairs and v_1 π^o-π^o pairs:

$$P_1(u_1,v_1) = e^{-\lambda_1}\lambda_1^{u_1+v_1}\left(\frac{2}{3}\right)^{u_1}\left(\frac{1}{3}\right)^{v_1}\Big/u_1!\,v_1! \tag{2-5}$$

We now let n_1 and m_1 be the number of negative and neutral pions produced respectively from σ clusters. From the respective decay modes, we obtain

* σ clusters by themselves cannot account for the experimentally observed rising value of $\langle n_o\rangle_{n_-}$ with n_- [1] or the non-zero value of $f_{-,-}^2$. There may be, however, an admixture of σ clusters together with other types.

$$m_1 = 2 v_1 \tag{2-6a}$$

$$\text{and} \qquad n_1 = u_1 \, . \tag{2-6b}$$

Thus the probability of producing n_1 negative pions and m_1 neutral pions is given by

$$P_1(n_1, m_1, s) = e^{-\lambda_1} \lambda_1^{n_1 + m_1/2} \left(\frac{2}{3}\right)^{n_1} \left(\frac{1}{3}\right)^{m_1/2} \Big/ n_1! \left(\frac{m_1}{2}\right)! \tag{2-7}$$

with n_1 taking on all integer values and m_1 restricted to even integers. The probability of negative pion production via σ clusters,

$$P_1(n_1, s) = \sum_{m_1} P_1(n_1, m_1, s) = e^{-2\lambda_1/3} \left(2\lambda_1/3\right)^{n_1} \Big/ n_1! \tag{2-8}$$

is needed for comparison with charged particle production data.

B. ρ-ρ Clusters

Following steps similar to those used for σ clusters, we first note that a ρ-ρ cluster can occur as a ρ^+-ρ^- pair or as a ρ°-ρ° pair with probabilities of 2/3 and 1/3 respectively. If $k_2 = u_2 + v_2$, we have from the above

$$P_2(u_2, v_2) = e^{-\lambda_2} \lambda_2^{k_2} \left(\frac{2}{3}\right)^{u_2} \left(\frac{1}{3}\right)^{v_2} \Big/ u_2! \, v_2! \tag{2-9}$$

as the probability of obtaining u_2 ρ^+-ρ^- pairs and v_2 ρ°-ρ° pairs. Since $\rho^\pm \rightarrow \pi^\pm \pi^\circ$ and $\rho^\circ \rightarrow \pi^+ \pi^-$, we can relate n_2 and

m_2, the numbers of negative and neutral pions produced due to decay of ρ-ρ clusters to u_2 and v_2:

$$n_2 = u_2 - 2v_2 \tag{2-10a}$$

and $$m_2 = 2u_2 \tag{2-10b}$$

The probability of obtaining n_2 π^-'s and m_2 π^0's by this process is therefore

$$P_2(n_2, m_2, s) = e^{-\lambda_2} \lambda_2^{n_2/2 + m_2/4} \left(\frac{2}{3}\right)^{m_2/2} \left(\frac{1}{3}\right)^{n_2/2 - m_2/4} \Big/ \left(\frac{m_2}{2}\right)! \left(\frac{n_2}{2} - \frac{m}{4}\right)! \tag{2-11}$$

where $n_2 = 0, 1, 2, \ldots$

$m_2 = 0, 2, 4, \ldots, 2n_2$.

The probability of producing n_2 negative pions by ρ-ρ clusters is given by

$$e^{-\lambda_2/2} \qquad \text{for} \quad n_2 = 0 \tag{2-12a}$$

$$P_2(n_2, s) = \frac{\left(\frac{2}{3}\lambda_2\right)^{n_2/2} e^{-\lambda_2}}{1\cdot 3\cdot 5 \cdots (n_2 - 1)} L_{n_2/2}^{(-\frac{1}{2})}\left(-\frac{\lambda_2}{3}\right) \qquad \text{for } n_2 = 2, 4, 6, \ldots \tag{2-12b}$$

$$\frac{\left(\frac{2}{3}\lambda_2\right)^{(n_2+1)/2} e^{-\lambda_2}}{1\cdot 3\cdot 5 \cdots (n_2)} L_{\frac{n_2-1}{2}}^{(\frac{1}{2})}\left(-\frac{\lambda_2}{3}\right) \qquad \text{for } n_2 = 1, 3, 5, \ldots \tag{2-12c}$$

where $L_N^{(\alpha)}(x)$ is the generalized Laguerre polynomial of degree N, index α, and argument x.

C. A_2-A_2 Clusters

As in the other clusters, the relative probability for charged and neutral pairs is binomial and the total number of A_2-A_2 clusters is Poisson. Thus, the probability for producing u_3 A_2^+-A_2^- pairs and v_3 A_2^o-A_2^o pairs is

$$P_3(u_3, v_3) = e^{-\lambda_3} \lambda_3^{u_3+v_3} \left(\frac{2}{3}\right)^{u_3} \left(\frac{1}{3}\right)^{v_3} \Big/ u_3!\, v_3! \tag{2-13}$$

The decay of a neutral A_2 has two possible branches to final state pions; however, both lead to the same final state:

$$A_2^o \rightarrow \begin{cases} \rho^+\pi^- \longrightarrow \pi^+\pi^o\pi^- \\ \pi^+\rho^- \longrightarrow \pi^+\pi^o\pi^- . \end{cases}$$

On the other hand, the two possible branches of the charged A_2 decay leads to different final states:

$$A_2^\pm \longrightarrow \begin{cases} \rho^\pm\pi^o \longrightarrow \pi^\pm\pi^o\pi^o \\ \pi^\pm\rho^o \longrightarrow \pi^\pm\pi^+\pi^- . \end{cases}$$

Since the relative probabilities of each branch are equal, a binomial distribution can be used to describe the decay. Therefore, the probability of u_3 A_2^+ producing r $\pi^+\pi^o\pi^o$ and (u_3-r) $\pi^+\pi^+\pi^-$ is

$$P_{u_3}(r, u_3-r) = \binom{u_3}{r}\left(\frac{1}{2}\right)^{u_3} \tag{2-14a}$$

and the probability of u_3 A_2^- producing w $\pi^-\pi^o\pi^o$ and (u_3-w) $\pi^+\pi^-\pi^-$ is

$$P_{u_3}(w, u_3-w) = \binom{u_3}{w}\left(\frac{1}{2}\right)^{u_3} . \tag{2-14b}$$

Thus, the probability for producing r - $\pi^+\pi^\circ\pi^\circ$, w - $\pi^-\pi^\circ\pi^\circ$ and v_3 A_2°-A_2° clusters is

$$P_3(r,w,v_3) = P_3(u_3,v_3)\,P_{u_3}(r,u_3-r)\,P_{u_3}(w,u_3-w)$$
$$= \frac{e^{-\lambda_3}\,\lambda_3^{u_3+v_3}\,u_3!\,\left(\frac{1}{6}\right)^{u_3}\left(\frac{1}{3}\right)^{v_3}}{r!\,(u_3-r)!\,w!\,(u_3-w)!\,v_3!}\,. \quad (2\text{-}15)$$

It is now easy to recognize that the numbers of negative and neutral pions, n_3 and m_3, are given by

$$n_3 = 3u_3 - r - w + 2v_3 \quad (2\text{-}16a)$$

and

$$m_3 = 2(r+w+v_3). \quad (2\text{-}16b)$$

Thus the probability for producing n_3 π^- and m_3 π° is

$$P_3(n_3,m_3,s) = \sum_{u_3,v_3,r,w} P_3(r,w,v_3)\,\delta_{n_3,3u_3-r-w+2v_3}\,\delta_{m_3,2(r+w+v_3)}$$

$$= e^{-\lambda_3}\sum_{u_3,r}\frac{u_3!\left(\frac{\lambda_3}{6}\right)^{u_3}\left(\frac{\lambda_3}{3}\right)^{\frac{n_3}{3}+\frac{m_3}{6}-u_3}}{\left(\frac{n_3}{3}+\frac{m_3}{6}-u_3\right)!\,r!\,\left(\frac{m_3}{3}-\frac{n_3}{3}-r+u_3\right)!\,(u_3-r)!\,\left(\frac{n_3}{3}-\frac{m_3}{3}+r\right)!} \quad (2\text{-}17)$$

where $u_3 = 0, 1, 2, \ldots, n_3/3 + m_3/6,$

$r = 0, 1, 2, \ldots, u_3,$

and n_3 and m_3 are restricted by the requirement that the arguments of the factorial functions be integers.

Finally, the distribution of negative pions is given by

$$P_3(n_3, s) = \sum_{m_3} P_3(n_3, m_3, s)$$

$$= e^{-\lambda_3} \sum_{u_3, v_3, r} \frac{u_3! \left(\frac{\lambda_3}{6}\right)^{u_3} \left(\frac{\lambda_3}{3}\right)^{v_3}}{v_3!\, r!\, (3u_3+2v_3-n_3-r)!(u_3-r)!(n_3+r-2u_3-2v_3)!} \qquad (2\text{-}18)$$

where the values of u_3, v_3, and r are again restricted by the arguments of the factorial functions.

D. Total Probability Distributions

Using the results of the preceding sections, we now form the probability function that describes the production of n negative pions and m neutral pions:

$$P(n, m, s) = \sum P_1(n_1, m_1, s) P_2(n_2, m_2, s) P_3(n_3, m_3, s) \times$$
$$\times \delta_{n, n_1+n_2+n_3} \quad \delta_{m, m_1+m_2+m_2} . \qquad (2\text{-}19)$$

The summation is over the variables n_1, n_2, n_3, m_1, m_2, and m_3 that take on all non-negative integral values allowed by the Kronecker deltas. The distributions $P_1(n_1,m_1,s)$, $P_2(n_2,m_2,s)$ and $P_3(n_3,m,s)$ are given by Eqs. (2-7), (2-11), and (2-17).

The comparison to experimental data is done with the probability distribution of negative pions:

$$P(n, s) = \sum_m P(n, m, s)$$
$$= \sum_{n_1, n_2, n_3} P_1(n_1, s) P_2(n_2, s) P_3(n_3, s)\, \delta_{n, n_1+n_2+n_3} \qquad (2\text{-}20)$$

where the values of n_1, n_2, and n_3 are similarly restricted. The probability distribution of each type of cluster is given by Eqs. (2-8), (2-12), or (2-18).

3. Fitting the Model to Experimental Data

Since our model describes only non-diffractive multiparticle production, it is necessary to subtract out diffractive events from the experimental data before a fit of the model is made. The method we used is based on an idea advanced by Wroblewski [16] in which he considered the modified Buras-Koba variables:

$$w' = \left(\frac{\pi}{4}\right)\left(\frac{n-1}{\langle n\rangle-1}\right)^2$$

and

$$\phi' = \frac{1}{\pi}\left(\frac{\langle n\rangle-1}{n-1}\right)^2 P_n \,. \qquad (3\text{-}1)$$

When the experimental data are plotted using these variables, Wroblewski noted that for $w' > 1$ they fall on the line

$$\ln \phi' = A - Bw'. \qquad (3\text{-}2)$$

He also noted that for low multiplicities (i.e., $w' \leq 1$), the data lay primarily above this line. He attributed this deviation to the occurrence of diffractive events that are known to populate low multiplicities. In using this idea to separate out diffractive events, we have calculated a minimum value of n for which $w' \geq 1$ for each set of data and then used only those data for which $n \geq n_{min}$.

The only adjustable parameters of the model a_1, a_2, and a_3 were determined by fitting to p-p data at laboratory momenta of 50, 69, 102, 205, 303, and 405 GeV/c. [17-21] Only the higher multiplicity data in each set were used as described above. The values of parameters obtained through this procedure are given in Table I.

Insert Table I here

The top row is the best fit utilizing all three parameters, while the second row is the best fit allowing for only ρ-ρ type clusters. It can be seen that A_2-A_2 clusters do not appear to be necessary, and that σ clusters do not change the accuracy of the fit significantly. It is noted that the accuracy of fit is not nearly as good as for some phenomenological models.

We next compare the predictions of our model, as fitted to the charged particle data, to the available charged and neutral particle data [22-25] at these momenta plus the ISR data. Specifically, we look at $\langle n_o \rangle_{n_-}$, the average number of neutral particles produced for a given number of negatives, and $f^2_{-,-}$, $f^2_{-,o}$, and $f^2_{o,o}$, the two particle correlation functions for two negative, one negative and one neutral, and two neutral pions. Figure 1 shows the experimental values, where available, as well as the theoretical values for the "best fit" and "best ρ-ρ only fit" for $\langle n_o \rangle_{n_-}$ as a function of n_-. Figure 2 illustrate theoretical values, "best fit" values, and "best ρ-ρ only fit" values of $f^2_{-,-}$, $f^2_{-,o}$, $f^2_{o,o}$, respectively, as functions of lab momentum.

4. Conclusion

The most important conclusion that we obtain from this study is that, if isoscalar cluster production is responsible for the non-diffractive particle production, ρ-ρ clusters predominate. The improvement in the fit to the data is negligible when we include σ clusters, and any admixture of A_2-A_2 clusters makes the fit much worse. ρ-ρ clusters have an average of 2.67 charged particles per cluster, compared with the experimental value of 2.0 to 2.5 reported by several authors [15]. The discrepancy could be due to the fact that we do not consider fragmentation produced clusters that may have a smaller average number of charged particles.

Looking at Fig. 1, we find no systematic discrepancies between the theoretical values for ρ-ρ + σ or ρ-ρ clusters and experimental values for $n_- \geq 3$ although there are several random discrepancies. When we look at values of $n_- \leq 2$ however, we find that the theoretical values are generally too small. (For example, for ρ-ρ clusters $\langle n_o \rangle_o = 0$.) This is to be expected, since we fit our model to the non-diffractive data and we should not expect it to predict low multiplicity events where diffraction effects are concentrated.*

When we look at Fig. 2, we find little data for $f^2_{o,o}$ and $f^2_{-,o}$. For $f^2_{-,-}$, we see that as a function of P_{lab}, the experimental values seem to rise much faster than the approximately logarithmic rise for the theoretical values. This might be explained by the fact that lower multiplicities have a proportionally greater number of diffractive events, which seem to behave like σ clusters. Since $f^2_{-,-} = 0$ for σ clusters (see Appendix), we would expect lower values for this quantity for energies where diffraction is proportionally more important. Thus, the faster than linear rise as we move away from these energies is ignored.

*We do not get the amount of oscillations in $\langle n_o \rangle_{n_-}$ for all values of n_- as reported in [4]. The authors made an error and got a value of $-\lambda_2/8$ instead of $-\lambda_2/3$ in their equation corresponding to (2-12). This much smaller value for the argument in the Laguerre Polynomials produces the reported oscillation.

A true test of this model awaits more accurate data, especially ISR data, as well as data capable of accurately differentiating between diffractive and non-diffractive events, as was done by Dao [26], where he uses a momentum transfer analysis to classify events. This type of data would allow the calculation of the purely non-diffractive contribution to $\langle n_o \rangle_{n_-}$ and the f^2's which could be compared to our model.

Another basis for testing our model could come from comparing the non-diffractive parts of $f^2_{-,-}$, $f^2_{o,-}$, and $f^2_{o,o}$. If only $\rho-\rho$ clusters are present, for example, these are in the ratio of 1:2:2. A comparison of values for the f^2's at a given energy could give information on which clusters predominate.

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APPENDIX

The integrated two-body correlation functions are defined by

$$f^2_{i,j} = \langle n_i n_j \rangle - \langle n_i \rangle \langle n_j \rangle \qquad i \neq j \qquad \text{(A-1a)}$$

$$= \langle n_i (n_i - 1) \rangle - \langle n_i \rangle^2 \qquad i = j \qquad \text{(A-1b)}$$

These quantities can easily be calculated for the three types of clusters in our model by expressing n_i and m_i, the numbers of negative and neutral pions, respectively, for each of the three cluster types in terms of the quantities in Eqs. (2-6), (2-10), and (2-16), and calculating the correlations using the probability functions (2-5), (2-9), and (2-15). The results of this calculation are shown in Table A-I.

Insert Table A-I here

It is easily seen that since $\langle n \rangle$ goes as λ_i these values are in agreement with the consequences of the short range correlation hypothesis [12] which requires all correlations to be of the form

$$f^k = a_k \langle n \rangle + b_k \qquad \text{(A-2)}$$

This result is not unexpected since the independent cluster model is a special case of models satisfying short range order.

TABLES

Table I Fitting of Data

a_1	a_2	a_3	Number of data points	χ^2	χ^2/data point
0.102	.451	0.0	53	408	7.422
0.0	.505	0.0	53	418	7.892

Table A-I

	$f^2_{-,-}$	$f^2_{-,0}$	$f^2_{0,0}$
σ clusters	0	0	$2\lambda_1/3$
ρ-ρ clusters	$2\lambda_2/3$	$4\lambda_2/3$	$4\lambda_2/3$
A_2-A_2 clusters	$7\lambda_3/3$	$2\lambda_3$	$10\lambda_3/3$

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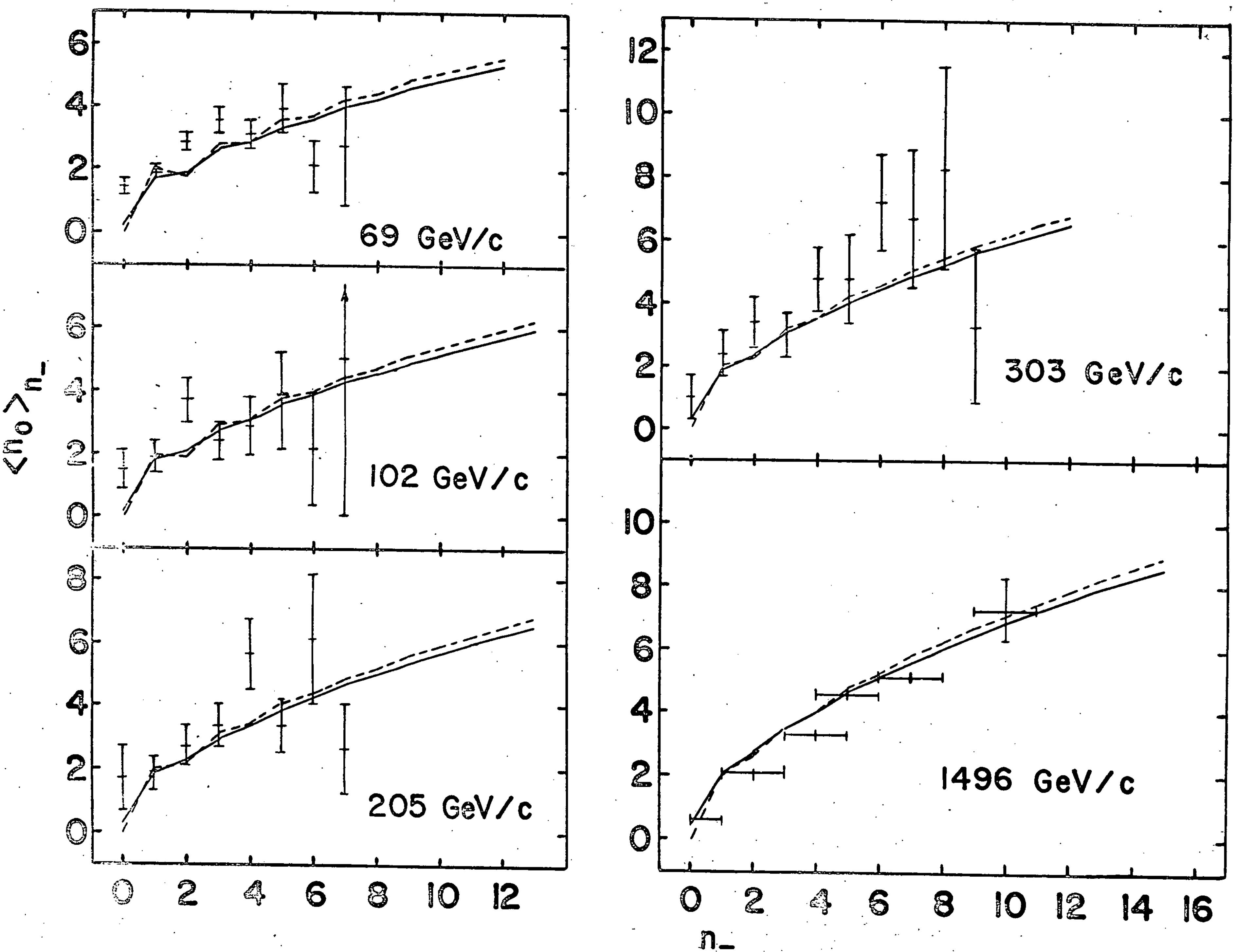
Figure Captions

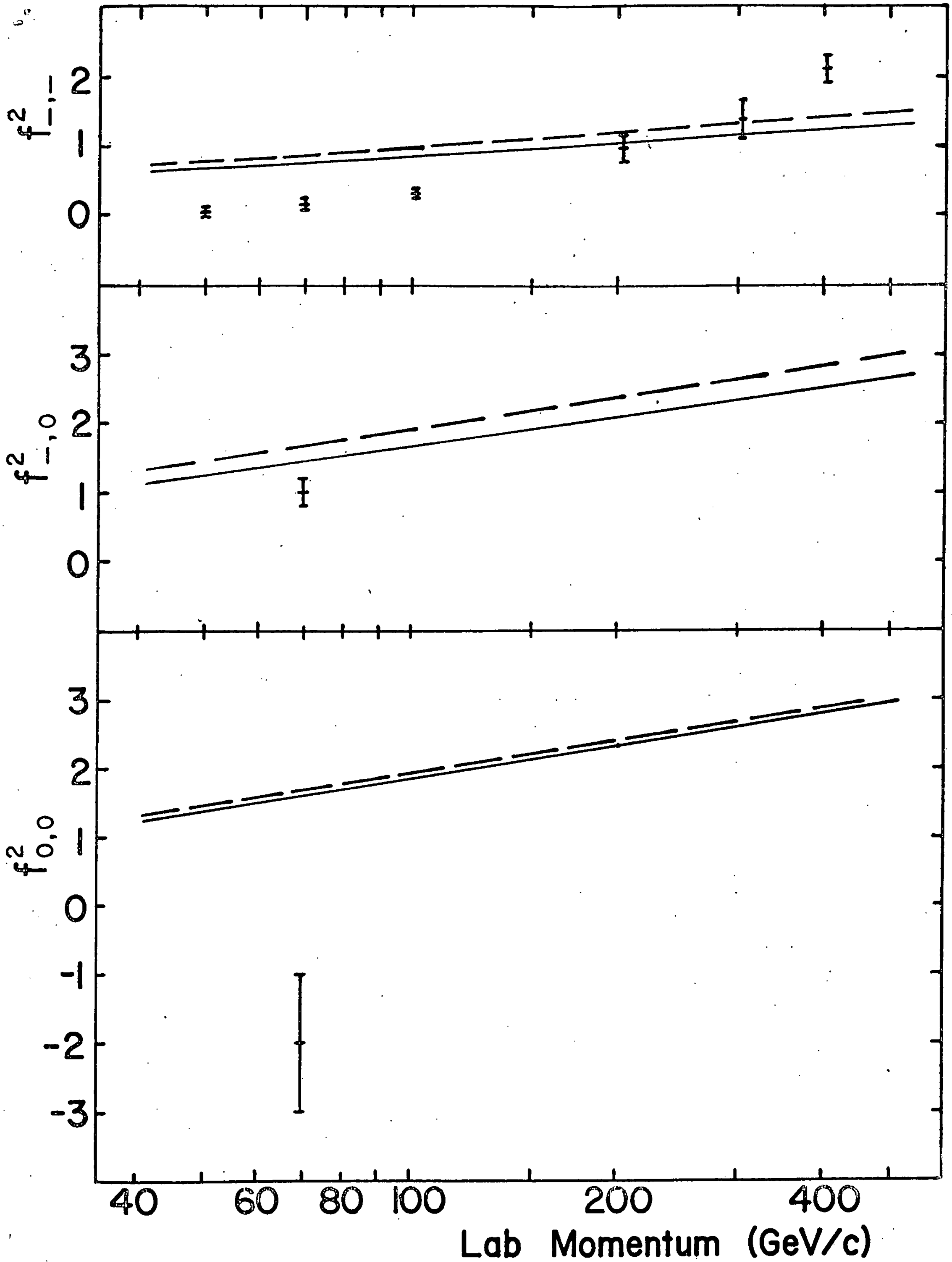
Figure 1. Average number of neutral particles per number of negative particles. Theoretical predictions are valid only at integer values of n_-. The lines are used to simplify the presentation. The solid line is the prediction of the " ρ-ρ and σ clusters" fit and the dashed line is the prediction of the " ρ-ρ clusters only" fit.

Figure 2. Integrated two particle correlation coefficients for p-p collisions as a function of incident laboratory momentum. The solid and dashed lines are the predictions of the model with ρ-ρ and σ clusters and only ρ-ρ clusters respectively.



69 GeV/c
102 GeV/c
205 GeV/c
303 GeV/c
1496 GeV/c
$\langle n_0 \rangle_{n_-}$
n_-

Figure 1



$f^2_{-,-}$
2
1
0
$f^2_{-,0}$
3
2
1
0
$f^2_{0,0}$
3
2
1
0
-1
-2
-3
40
60
80
100
200
400
Lab Momentum (GeV/c)

Figure 2